AMENDMENT OF THE SPECIFICATION:

On page 10 of the specification, beginning with the last paragraph, which begins with the sentence, "In order for the S and P maxima to coincide, equation (4) below must be satisfied." amend the page as follows:

In order for the S and P maxima to coincide, ~~equation (4) below must be satisfied.~~ the values of Es and Ep from equations (2) and (3) must be simultaneously equal to 1. Es will be equal to 1 when $\upsilon = \frac{2s-1}{2}\pi$ and Ep will be equal to 1 when $\upsilon\cos(2\theta) = \frac{2p-1}{2}\pi$, where s and p are integers, 1, 2, 3, ... The value of $\cos(2\theta)$ at which the Es and Ep maxima coincide can be found by simply solving the above two equations for $\cos(2\theta)$. The result is equation (4) below. ~~The value of the index modulation, Δn, at which the S-polarization diffraction efficiency is maximum, for a given wavelength, index of refraction of the medium and effective thickness of the medium, is given by equation (5). Therefore, when these two equations are satisfied simultaneously, the S and P diffraction efficiencies will be maximized simultaneously.~~

(4) $\cos(2\theta) = (2p-1)/(2s-1)$

(Since the cosine of an angle cannot be greater than 1 for any real angle, the integer, p, must always be less than the integer, s, in equation (4).)

~~(5)~~ $\cancel{\Delta nT/\lambda = (2s-1)[\sqrt{(C_R C_S)}]/2}$

where

s is the order of the S diffraction efficiency peak (1, 2, 3, ...) and p is the order of the P diffraction efficiency peak (1, 2, 3, ...)

θ is the angle between the incident beam and the Bragg planes inside the medium (A Bragg plane is a plane of maximum refractive index in the medium)

2θ is the angle between the incident beam and the diffracted beam inside the medium

~~The remaining parameters are defined following Eq. (1)~~

Equation (1) can be re-arranged to provide an equation for the index modulation:

$$\Delta n = \frac{\upsilon \lambda}{\pi T}\sqrt{C_R C_S}.$$

But from the derivation of Equation (4) above we know that

$$\upsilon = \frac{2s-1}{2}\pi$$

when Es is maximum. Therefore, when Es is maximum,

$$\Delta n = \frac{\lambda}{T}\left(\frac{2s-1}{2}\right)\sqrt{C_R C_S}$$

where

$$C_R = \cos\alpha$$

$$C_S = \cos\alpha - \frac{\lambda}{nd}\tan\left(\frac{\beta-\alpha}{2}\right)$$

(See Kogelnik, H. "Coupled Wave Theory for Thick Hologram Gratings," Bell System Technical Journal, Vol. 48, No. 9, 1969, Equation 23)

The final result is:

$$\text{(5)}\quad \Delta n = \frac{\lambda}{T}\frac{2s-1}{2}\sqrt{C_R C_S} = \frac{\lambda}{T}\left(\frac{2s-1}{2}\right)\sqrt{(\cos\alpha)\left(\cos\alpha - \frac{\lambda}{nd}\tan\left(\frac{\beta-\alpha}{2}\right)\right)}$$

where all terms have been previously defined.

So the value of the index modulation, Δn, at which the S-polarization diffraction efficiency is maximum, for a given wavelength, index of refraction of the medium and effective thickness of the medium, is given by equation (5). Therefore, when equations (4) and (5) are satisfied simultaneously, the S and P diffraction efficiencies will be maximized simultaneously.

From Figure 2 it can be seen that $\alpha + \beta = 2\theta$, so that Equation (4) can be solved for β, the internal angle of diffraction, to yield:

$$(6)\ \beta = a\cos\left(\frac{2p-1}{2s-1}\right) - \alpha$$

~~For example, at the first possible coincidence of the two diffraction peaks p = 1 and s = 2.~~

~~Then $\cos(2\theta) = \frac{1}{3}$ and $2\theta = 70.53\deg.$ and $\theta = 35.26\deg.$~~

Therefore, for given values of the bulk refractive index, n, effective thickness, T and wavelength, λ, and arbitrarily selected values of the integers s and p and the internal angle of incidence, α, the value of the internal angle of diffraction, β, established by Eq. (6) and the value of the index modulation, Δn, established by Eq. 5 will result in simultaneously maximizing the S-polarization diffraction efficiency, Es, and the P-polarization diffraction efficiency, Ep, at a common value of the index modulation, Δn.

This coincidence of the sth peak of the S-polarization diffraction efficiency curve and the pth peak of the P-polarization diffraction efficiency curve at a common value of the index modulation, Δn, is the major novel property of the Enhanced Volume Phase Grating. Figure 7 is an example of an Enhanced Volume Phase Grating where the third peak of the S-polarization diffraction efficiency curve coincides with the second peak of the P-polarization diffraction efficiency curve at an index modulation value of 0.21.

Note that coincidence of the sth peak of the S diffraction efficiency curve and the pth peak of the P diffraction efficiency curve will also occur when the following equation for β is satisfied:

$$\cancel{(6)\ \cos 2(90-\theta)} = \frac{2p-1}{2s-1}$$

$$(7)\ \beta = 180 - a\cos\left(\frac{2p-1}{2s-1}\right) - \alpha$$

That is, the S and P efficiency peaks will coincide when the angle between the incident beam and the Bragg planes inside the medium is either θ or $90-\theta$. In other words, the two angles will lie equally to either side of the zero-P-efficiency angle of 45 degrees.

~~In the example above, where p = 1 and s = 2, we have for the second angle:~~

$$\cancel{2\theta = 109.47\,\text{deg} \quad \text{and} \quad \theta = 54.74\,\text{deg}.}$$

~~Since, in this case, the second angle is larger than the first angle, the dispersion will be greater and the effective thickness, T, will be less (for a given index modulation, Δn).~~

The second angle will generally exceed the internal angle of total internal reflection (TIR) if the substrate is parallel to the VPG medium and the external medium is air. This problem can be overcome by using a dual-prism grism design such as that shown in Fig. 11. This type of design allows the angles of incidence and diffraction inside the medium to exceed the normal TIR angle.

The required value of the index modulation, Δn, will be dependent on the effective thickness, T, the wavelength, λ, and the two obliquity factors, C_R and C_S. The values of the obliquity factors will be dependent on the bulk index of the medium and the external angles of incidence and diffraction, as established by the Kogelnik theory.

DESIGNING AN ENHANCED VOLUME PHASE GRATING IN ACCORDANCE WITH THE PRESENT INVENTION

As an example of the design process for an Enhanced Volume Phase Grating, consider the simplest case, where s = 2 and p = 1. Not only is this the simplest E-VPG design, it is also the easiest E-VPG to fabricate and is, therefore, the most likely E-VPG to be used in practice.

Note that the selection of the integer values of s and p is completely arbitrary, so long as s > p. The design process would be identical for any combination of s and p integers. E-VPGs resulting from a selection of larger values of s and p would have greater dispersion but would be more difficult to fabricate and would require the use of external prisms.

Once s and p are selected (2 and 1 in this example), the angle of incidence, θ_i, must be selected. The angle of incidence, θ_i, can be selected to provide a symmetric grating design, where the angle of diffraction, θ_d, is equal to the angle of incidence, θ_i, or a non-symmetric grating design, where the angle of diffraction, θ_d, is not equal to the angle of incidence, θ_i. The choice is generally governed by other factors in the overall system design.

Once θ_i is established, the internal angle of incidence, α, can be determined using the well known Snell's Law and the known bulk refractive index, n, of the volume phase medium. Then, once this internal angle of incidence, α, is determined, equation (6) can be used to establish the internal angle of diffraction, β. Then Snell's Law can be used to determine the external angle of diffraction, θ_d.

Knowing the internal angle of incidence, α, the internal angle of diffraction, β, the bulk refractive index, n, of the volume phase medium and the free space wavelength, λ, of the incident beam, one can use the following equation, which is a transposition of the grating equation noted earlier, to determine the grating period, d:

(8) $$d = \frac{\lambda}{n(\sin\alpha + \sin\beta)}.$$

Furthermore, knowing the external angle of incidence, θ_i, and the external angle of diffraction, θ_d, the construction illumination geometry of the E-VPG can be established. In fact, if the application wavelength and the construction wavelength for the E-VPG are the same, then θ_i and 180 + θ_d will be the construction angles for the laser beams used in constructing the E-VPG. If the construction wavelength is not the same as the application wavelength, as is often the case, then the construction angles must be modified in accordance with procedures that are well known in the art of fabrication of volume phase gratings (See, for example, the following US patents: US 6,085,980 and US 6,112,990).

The final step in the fabrication process of the E-VPG is to expose and process the E-VPG so that the peak index modulation, Δn, is equal to the value calculated in equation (5). Exposure and processing methods to accomplish this are well known in the art (See, for example, Chang, M. "Dichromated Gelatin of Improved Quality", Applied Optics, Vol. 10, p. 2250, 1971 and Meyerhofer, D. "Phase Holograms in Dichromated Gelatin," RCA Review, Vol. 35, p. 110, 1972.)

Note: In an alternative design process, one can select a value for the external angle of diffraction, θ_d, and use Snell's Law to determine the internal angle of diffraction, β, equation (6) to determine the internal angle of incidence angle, α and Snell's Law to determine the external angle of incidence, θ_i. The construction process and the

procedure to establish the peak index modulation, Δn, would be the same as for the case where the angle of incidence, θ_i, was selected at the outset.

Satisfying ~~these~~ equations (5) and (6) ~~alone~~ is sufficient to obtain high diffraction efficiency for both polarizations simultaneously. And the angles needed to satisfy the ~~first~~ second of these two equations will result in high dispersion. However, there is a fourth requirement for a WDM grating that has made the accomplishment of the present invention heretofore impossible. The WDM application requires low insertion loss and low PDL across the full width of one of the telecommunications passbands. That is, for the C band, the insertion loss and the PDL must be acceptably low over the full wavelength range from 1528 nm to 1565 nm. That is impossible to achieve in a conventional VPG because of the high Bragg angle sensitivity that would result when the necessary equations are satisfied. Bragg angle sensitivity is the variation of diffraction efficiency as a function of either the wavelength or the angle of incidence of the incident beam.

CLEAN VERSION OF AMENDED PAGES OF THE SPECIFICATION - STARTING WITH PAGE 10.
(The following clean pages replace pages 10 through 12 in the original application)

then choose to operate at the peak of the S diffraction efficiency curve so that the insertion loss for S-polarization will be low. However, since the P diffraction efficiency is low at this value of Δn, the PDL will be very high.

In a third case, the angles are increased to provide very high dispersion so that we have the situation shown in Fig. 4. However, in this case, the choice is made to operate at the crossover point of the two curves in order to minimize the PDL. But both the S and P diffraction efficiencies will be low at this value of Δn. The net result is that this approach will provide very high dispersion and low PDL but very high insertion loss.

So the three cases just described will provide (1) low insertion loss and low PDL but low dispersion; (2) low insertion loss and high dispersion but large PDL; (3) high dispersion and low PDL but very high insertion loss. None of these three situations is optimum for WDM applications. What is desired is (a) high dispersion and (b) low insertion loss and (c) low PDL.

One can achieve this desired combination if the angles of incidence and diffraction are selected so that the P diffraction efficiency curve reaches its first maximum when the S diffraction efficiency curve reaches its second maximum. This situation is shown in Fig. 6. In this case, the S and P diffraction efficiencies are both equal and both maximum so that the PDL is minimized. In addition, the angles at which this equalization occurs are relatively large so that the dispersion is also large. The net result is that the insertion loss is low, the PDL is low and the dispersion is high. That is, we have the desired combination of all three major grating parameters.

One can increase the dispersion even further by increasing the angles of incidence and diffraction until S and P maxima farther out along the Δn axis coincide. For example, one can select angles of incidence and diffraction so that the third peak of the S diffraction efficiency curve coincides with the first or second peak of the P diffraction efficiency curve, as shown in Fig. 7. This will provide greater dispersion and it will also allow the effective thickness, T, to be reduced (for a given index modulation, Δn). Higher order combinations are also possible but these combinations may be more difficult to fabricate.

In order for the S and P maxima to coincide, the values of Es and Ep from equations (2) and (3) must be simultaneously equal to 1. Es will be equal to 1 when $\upsilon = \frac{2s-1}{2}\pi$ and Ep will be equal to 1 when $\upsilon\cos(2\theta) = \frac{2p-1}{2}\pi$, where s and p are integers, 1, 2, 3, ... The value of $\cos(2\theta)$ at which the Es and Ep maxima coincide can be found by simply solving the above two equations for $\cos(2\theta)$. The result is equation (4) below.

(4) $\cos(2\theta) = (2p-1)/(2s-1)$

(Since the cosine of an angle cannot be greater than 1 for any real angle, the integer, p, must always be less than the integer, s, in equation (4).)

where

s is the order of the S diffraction efficiency peak (1, 2, 3, ...) and p is the order of the P diffraction efficiency peak (1, 2, 3, ...)

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$$\Delta n = \frac{\upsilon\lambda}{\pi T}\sqrt{C_R C_S}\ .$$

But from the derivation of Equation (4) above we know that

$$\upsilon = \frac{2s-1}{2}\pi$$

when Es is maximum. Therefore, when Es is maximum,

$$\Delta n = \frac{\lambda}{T}\left(\frac{2s-1}{2}\right)\sqrt{C_R C_S}$$

where

$$C_R = \cos\alpha$$

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(See Kogelnik, H. "Coupled Wave Theory for Thick Hologram Gratings," Bell System Technical Journal, Vol. 48, No. 9, 1969, Equation 23)

The final result is:

(5) $\Delta n = \frac{\lambda}{T}\frac{2s-1}{2}\sqrt{C_R C_S} = \frac{\lambda}{T}(\frac{2s-1}{2})\sqrt{(\cos\alpha)(\cos\alpha - \frac{\lambda}{nd}\tan(\frac{\beta-\alpha}{2}))}$

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So the value of the index modulation, Δn, at which the S-polarization diffraction efficiency is maximum, for a given wavelength, index of refraction of the medium and effective thickness of the medium, is given by equation (5). Therefore, when equations (4) and (5) are satisfied simultaneously, the S and P diffraction efficiencies will be maximized simultaneously.

From Figure 2 it can be seen that $\alpha + \beta = 2\theta$, so that Equation (4) can be solved for β, the internal angle of diffraction, to yield:

(6) $\beta = a\cos\left(\frac{2p-1}{2s-1}\right) - \alpha$

Therefore, for given values of the bulk refractive index, n, effective thickness, T and wavelength, λ, and arbitrarily selected values of the integers s and p and the internal angle of incidence, α, the value of the internal angle of diffraction, β, established by Eq. (6) and the value of the index modulation, Δn, established by Eq. 5 will result in simultaneously maximizing the S-polarization diffraction efficiency, Es, and the P-polarization diffraction efficiency, Ep, at a common value of the index modulation, Δn.

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That is, the S and P efficiency peaks will coincide when the angle between the incident beam and the Bragg planes inside the medium is either θ or $90-\theta$. In other words, the two angles will lie equally to either side of the zero-P-efficiency angle of 45 degrees.

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Once s and p are selected (2 and 1 in this example), the angle of incidence, θ_i, must be selected. The angle of incidence, θ_i, can be selected to provide a symmetric grating design, where the angle of diffraction, θ_d, is equal to the angle of incidence, θ_i, or a non-symmetric grating design, where the angle of diffraction, θ_d, is not equal to the angle of incidence, θ_i. The choice is generally governed by other factors in the overall system design.

Once θ_i is established, the internal angle of incidence, α, can be determined using the well known Snell's Law and the known bulk refractive index, n, of the volume phase medium. Then, once this internal angle of incidence, α, is determined, equation (6) can be used to establish the internal angle of diffraction, β. Then Snell's Law can be used to determine the external angle of diffraction, θ_d.

Knowing the internal angle of incidence, α, the internal angle of diffraction, β, the bulk refractive index, n, of the volume phase medium and the free space wavelength, λ, of the incident beam, one can use the following equation, which is a transposition of the grating equation noted earlier, to determine the grating period, d:

$$(8)\ d = \frac{\lambda}{n(\sin\alpha + \sin\beta)}.$$

Furthermore, knowing the external angle of incidence, θ_i, and the external angle of diffraction, θ_d, the construction illumination geometry of the E-VPG can be established. In fact, if the application wavelength and the construction wavelength for the E-VPG are the same, then θ_i and 180 + θ_d will be the construction angles for the laser beams used in constructing the E-VPG. If the construction wavelength is not the same as the application wavelength, as is often the case, then the construction angles must be modified in accordance with procedures that are well known in the art of fabrication of volume phase gratings (See, for example, the following US patents: US 6,085,980 and US 6,112,990).

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Satisfying equations (5) and (6) is sufficient to obtain high diffraction efficiency for both polarizations simultaneously. And the angles needed to satisfy the second of these two equations will result in high dispersion. However, there is a fourth requirement for a WDM grating that has made the accomplishment of the present invention heretofore impossible. The WDM application requires low insertion loss and low PDL across the full width of one of the telecommunications passbands. That is, for the C band, the insertion loss and the PDL must be acceptably low over the full wavelength range from 1528 nm to 1565 nm. That is impossible to achieve in a conventional VPG because of the high

Bragg angle sensitivity that would result when the necessary equations are satisfied. Bragg angle sensitivity is the variation of diffraction efficiency as a function of either the wavelength or the angle of incidence of the incident beam.

In a conventional VPG, Δn is typically in the range of 0.05 to 0.08. In order to satisfy equation (5) an effective thickness on the order of 25 to 35 microns would be required. It is well known that Bragg angle sensitivity is a strong function of the effective thickness of the medium. Fig. 8 shows the variation of S and P diffraction efficiencies for an effective medium thickness of 35 microns. The Bragg angle sensitivity is quite large and the resulting PDL at the ends of the passbands is totally unacceptable for WDM applications.

The present invention solves this final problem by exposing and processing the medium (DCG, in this case) to get a Δn on the order of 0.2 or greater. Processing procedures for DCG are well known in the art and processing for high Δn, while difficult, is an extension of known DCG processing methods.

In a typical embodiment of the present invention, the medium (DCG) is spin coated on a glass or fused silica substrate to a physical thickness that is on the order of 15 microns. It is exposed in a conventional dual-beam holographic grating fabrication process using a laser with a wavelength to which the DCG is responsive. It is then processed in a sequence of alcohol water baths using well-known DCG processing procedures. After drying and edge stripping to provide an adhesive o-ring seal when capped, the actual gratings are then diced from the larger grating, and then sealed (capped) with a cover glass.

In this particular embodiment of the present invention, the exposure and processing of the grating will yield a final effective thickness of approximately 9 to 10 microns.

Fig. 9 shows the S and P diffraction efficiency curves for one example of an Enhanced Volume Phase Grating of the present invention with an effective thickness of 9 microns and with the angles of incidence and diffraction selected to satisfy equation (4). The